

Consumer-side actions in a low-carbon economy: A dynamic CGE analysis for Spain

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ABSTRACT

In recent decades, the need to strengthen efforts to reduce GHG emissions to combat Climate Change has become a major global concern, as reflected in the 2015 Paris Agreement and the EU Climate strategy (2016). In this context, EU countries are required to organize their contributions to environmental improvement through national strategies. Given the potential importance of demand-side actions, both directly and through their relationship with the productive system, as well as the need for a dynamic evolution, we assess the dynamic path and medium-term environmental impact of certain consumer-oriented measures, using a dynamic Computable General Equilibrium (CGE) model. Specifically, we generate scenarios that follow Spain's strategies and evaluate the dynamic impact of more efficient technologies on electricity consumption and the use of transport services, both in terms of environmental (GHG and SO_x) and economic effects. Our results confirm the role of technology improvements in delivering positive results for the environment, and the importance of economy-wide rebound effects, through a detailed study of energy uses as a result of efficiency improvements in household energy consumption. Our findings show that reductions in emissions per person are consistent with economic growth.

1. Introduction

In recent decades, developed countries have made important investments in technology aiming to increase energy efficiency, both in productive activities and in energy use by households. Most of the electrical appliances sold today in Europe offer significant improvements in energy efficiency, and the promotion of public transport systems with greater fuel efficiency has played a prominent role in institutional environmental campaigns at the national and international levels. The EU climate strategy, EU (2016), aims to achieve an economy-wide GHG reduction target of at least 20% by 2020, compared to 1990, 40% by 2030, and 80% by 2050, and has set emissions ceilings for 2020 for each European Union (EU) member state (Directive, 2012/27UE), under which countries are required to organize their contributions to environmental improvement through national strategies.¹ In this context, the goal of Spain's current Energy Efficiency Action Plan (2014–2020) (NEEAP, 2014–2020) is to reduce energy consumption – and thus greenhouse gas (GHG) emissions – by 20% by 2020, following the methodological recommendations on savings, measurement, and verification of the European Commission. The Spanish Plan has the objective of improving final energy intensity by around 2% year-on-

year for the period 2010–2020, focusing efforts on six sectors of the economy (Industry, Transport, Building (residential and service), Equipment (residential and service), Public Services, and Agriculture and fisheries), with specific measures for each of the direct, indirect, and end-users involved. The objectives for 2030 will be designed under a new Plan in line with the goals of the EU.

An important part of the discussion in the literature has focused on the effects of technology and efficiency improvements implemented on the production side, rather than the consumer side. However, there is an increasing recognition that the responsibility for atmospheric emissions is not solely associated with producers, but also with the end-users of goods (Lenzen et al., 2007; Wiedmann et al., 2007; Hubacek et al., 2014; Cadarso et al., 2015; Hubacek et al., 2016; Feng and Hubacek, 2016; Schandl et al., 2016). Consumer actions have effects on production and related emissions, and thus a key question emerges: can gradual changes in household consumption patterns produce significant impacts on total emissions in the medium-term? We aim to address this question, looking at 2030.

More specifically, we assess the medium-term (up to 2030) environmental impact on the Spanish economy of certain consumer-oriented measures that are consistent with proposals of the Spanish

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¹ The EU's emissions for 2005 are slightly lower than those of 1990, and we use emissions in 2005 as the reference point, in line with EU targets.

“Energy Efficiency Action Plan”, exploring representative dynamic scenarios for a longer period, 2005–2030, and involving individual consumers. Hence, we analyse the impact of successive improvements, up to 2030, in household electricity savings (for lighting per dwelling and electrical appliances) and the promotion of efficient modes of transport (lower-fuel-consumption vehicles). We aim to test whether it will be possible to achieve the 2030 EU objectives, which focus on an energy consumption reduction of 40% or more.

A dynamic framework is essential in order to better capture the transition towards 2030 targets, the medium-term rebound effects, and their evolution over time. Our work uses a recursive dynamic Computable General Equilibrium (CGE) model, calibrated on 2005 Spanish data and dynamically extended for the period 2005–2030. We assume that the generalization of the implementation of improvements among citizens from 2005 to 2030 is low in the initial period, with a temporal progression characterized by an intermediate acceleration and smooth growth after a certain number of periods. We thus propose (as a novelty in the literature) a logistic schedule to capture this gradual adaptation. Moreover, this evolution is based on the real evolution of energy use from 2005 to 2015.

CGE models are multi-sector macroeconomic tools, used to simulate the ultimate result of such improvements, allowing us to capture changes in prices, investment, consumption, production, trade, and technology. Using a dynamic CGE model, we can also evaluate the time-consistency of environmental outcomes and the socio-economic (unemployment, welfare, production) effects of potential consumption choices of citizens.

Additionally, this work aims to contribute to the literature on rebound effects with a dynamic extension, given that, to the best of our knowledge, this is the first work to empirically measure the rebound effects associated with a logistic evolution of the improvements in the efficiency of household energy use. We also explore whether emissions related to household energy savings are compensated over time by potential spending of the additional income available from reductions in energy consumption.

From an empirical point of view, our analysis focuses on Spain, a middle-income ranked EU Member State, and on greenhouse gases (GHG) and sulphur oxide (SO_x).² We present the evolution and trends obtained from a dynamic model that considers the behaviour of more than 44 million people (the Spanish population) that can be highly representative of the gradual adaptation of consumers to new challenges for sustainable development in a wide range of developed countries.

In summary, this paper presents a full study of the implications of successive changes in consumption patterns, in terms of environmental and economic impacts for the whole economy (household and industrial uses of energy, rebound effects, jobs, macroeconomic results, GHG and SO_x emissions) with a global view of impacts. In other words, we address the following general question: To what extent could successive environmentally-positive changes in household consumption patterns lead to a large reduction of emissions in society as a whole, thus meeting environmental mandates?

The rest of the paper is organized as follows. Section 2 presents a brief review of prior work in this area. Section 3 sets out our methodology and data. Section 4 describes the 2005 pollution structure of the Spanish economy, our simulations, and the results obtained. Section 5 addresses sensitivity analyses of different assumptions for technological change, emissions data, and elasticity of substitution. Finally, Section 6 closes the paper with our concluding remarks.

2. Literature review

Alongside the input-output literature on carbon emissions and

environmental footprints, which mainly recognize the multi-sectoral nature of environmental impacts and the links between the consumption and the production perspectives (see for instance Lenzen et al., 2007; Wiedmann et al., 2007; Hubacek et al., 2014; and Duarte et al., 2010; Cadarso et al., 2015 for Spain, amongst others), CGE models have also been developed to assess the environmental impacts of consumption patterns, which allow for greater flexibility in modelling consumer behaviours and price reactions, as well as the capture of potential rebound effects. For instance, Dai et al. (2012) examine impacts on total energy use and emissions from changes in consumption patterns of Chinese households from high fossil fuel and carbon-intensive behaviour, to low fossil fuel and carbon-extensive behaviour towards 2050, using a dynamic CGE model. They reveal the importance of paying attention to demand-side countermeasures. Lecca et al. (2014) explore the rebound effects of increased energy efficiency in the household sector of the United Kingdom. Their results show a net expansion in the UK economy, with increases in investment, employment, and household spending. Duarte et al. (2016) use a static CGE model calibrated for Spain, and evaluate the effects of changes in the environmental awareness of Spanish consumers of different income levels. Their results suggest that reductions in emissions may be compatible with increases in income and reductions in unemployment. Figus et al. (2016) analyse the economy-wide impacts of improvements in Scottish household energy efficiency that lead to stimulation of the economy of the region. Tian et al. (2016) investigate the effects of household consumption pattern for a mega-city in the developing world, employing a CGE for the Shanghai economy. Figus et al. (2017) analyse the sustained added value to the UK economy by improving energy efficiency in the residential sector through government support at different income levels.

In the context of this literature, our paper is, to the best of our knowledge, the first study to evaluate changes in consumption choices and their gradual adaptation by citizens, in terms of emissions, using a logistic evolution. The use of logistic curves provides S-shaped patterns, which have been widely used in the literature to model different processes of innovation diffusion (Mansfield, 1961; Mahajan and Peterson, 1985; Kijek and Kijek, 2010). Our work involves a new use of these functions to approximate to the generalization of improvements among citizens that is low at the outset, with a temporal progression characterized by an intermediate acceleration and smooth growth after a certain number of periods (S-shaped pattern). This assumption allows us to achieve a better approximation of the effects of the generalization of improvements, an evaluation of the rebound effects triggered by technical change, and a greater understanding of economy-wide impacts and their evolution. Thus, our work benefits from the prior literature, and attempts to go further into the analysis of changes in consumption, in electricity use, and in the transport sector, through a dynamic CGE model that includes technological progress as a logistic evolution, to capture the gradual adaptation of citizens to policy targets.

The rebound effect has been broadly studied via CGE models, finding evidence that these effects may reduce the positive environmental results of efficiency improvements (see Hanley et al., 2006; Anson and Turner, 2009 for Scotland, using a dynamic CGE model; Barker et al., 2007 for the UK economy; Barker et al., 2009 for the world economy; Turner and Hanley, 2011 for the Scottish economy, and Koesler et al., 2016 for the global economy). Our work follows the recent rebound measures proposed in Lecca et al. (2014) and Koesler et al. (2016) to measure the economy-wide rebound effects of logistic improvements in the efficiency of household energy use.

3. Methodology

A dynamic CGE model is developed for the Spanish economy and calibrated using the Spanish Input-Output Framework (symmetric IOFA-05) available from INE (2005a). This section outlines the model

² We also analyse impacts on SO_x emissions due to their local effects, to approximate better to the regional impact.

used, and a list of indices, parameters, variables, and equations is shown in [Appendix A \(Supplementary information, SI\)](#).

The model describes an economy with 34 economic activities, two factors of production (labour and capital), and such other accounts as Households, Companies, Savings/Investment, Government, and a Foreign Sector. In line with the objective of our study, we take a special interest in energy, disaggregated into four sectors: coal, refined petroleum products, electricity, and gas. This level of disaggregation, focusing on sectors linked to energy, allows us to consider specific production structures according to certain substitution assumptions.

In our analysis, we develop a multi-sector, recursive dynamic CGE model for the Spanish economy. In a recursive model, decisions on production, consumption, and investment are taken, following prices, in the decision period. In other words, in each period we have a new equilibrium adapting the changes (energy and technical improvements, parameter changes, ...) introduced in that period, assuming bounded rationality. This differs from an inter-temporal model with the rational expectations of agents over a longer or infinite horizon.

[Fig. 1](#) represents the supply and demand sides of our dynamic model. Total output is earmarked to domestic or foreign demand through a Constant Elasticity of Transformation (CET) function. We include an Armington approach, in which domestic and imported goods are imperfect substitutes with different elasticities, and are attributed to all the components of final demand. We consider two external regions: the rest of the European Union (EU), and the rest of the world (ROW). One closure rule works between Spain and the rest of the European Union, whose exchange rate is fixed as the *numeraire*, while trade balance adjusts, as they trade in euros. A second closure rule operates between these regions and ROW, and also keeps the exchange rate constant. We pay special attention to the nesting structure of household consumption, following our interest in household energy use, and consumer choices. Consumer preferences are defined by a three-stage nested Constant Elasticity of Substitution (CES) utility function. In the case of the transport services aggregate, consumers choose the mean of transport between private car (petroleum use) and the remaining transport services. Each year, all agents spend their income on consumption, transfers, taxes, and investments. Total public expenditure is modelled through a fixed-coefficients structure. Lump-sum transfers between the government and the consumer are endogenously adjusted to ensure the same level of public spending. Finally, total investment equals total savings by all institutions.

The specification of the nesting production structure is similar to the GTAP-E model ([Burniaux and Truong, 2002](#)), which focuses on the combination of non-energy intermediate inputs and the composite of value-added and energy input, which is also a CES combination of the capital factor and the energy composite. In the following stages, nested functions are modelled for the energy selection, as presented in [Fig. 1](#). The elasticity parameters are selected on the basis of a review of the literature on this topic and presented in [Table A5 in Appendix A of the SI](#).

Regarding factor markets, we consider the labour factor to be mobile across sectors, while capital is immobile. However, as social indicators are increasingly sought, the model also includes a wage curve to consider unemployment, following [Blanchflower and Oswald \(1990\)](#). Finally, we calibrate these nesting structures to the Spanish data, in line with the corresponding parameters and coefficients provided by the input-output table.

The model above is calibrated for the Spanish economy of 2005, and dynamically extended for the period 2005–2030, following [Paltsev \(2000\)](#) and [Sarasa \(2014\)](#), with successive balances from 2005 to 2030 (see the detailed equations of capital stock growth in [Appendix A of the SI](#)). The values of the main parameters of the dynamic model are obtained from actual average data for Spain in the period 2005–2015 ([INE, 2005–2015a, 2005–2015b](#)). Specifically, the annual interest rate

is 4.22% and the growth rate is 0.77%.³ The relationship between capital and investment in the initial steady-state is obtained from the calibration of the model using the information of the Spanish input-output table. The model is programmed as a mixed complementarity problem (MCP) using GAMS/MPSGE ([Rutherford, 1999](#)) and is solved with the PATH algorithm.

Technological change, represented by φ_t , is included in the CES household consumption function (see [Eqs. \(A16\) and \(A18\)](#)) shown in [Appendix A of the SI](#), according to our simulations to define the effective electricity use and the effective fuel use. More importantly, we consider the generalization of efficiency improvement as a learning process. Thus, we consider a logistic evolution following a Gompertz function, to represent the gradual upward improvement from 2005 to 2030.⁴ (See details of the technological improvements implemented in the following Section).

Once the main economic and environmental impacts are obtained, the input-output model is used in the attribution of emissions to final demand (see also [Turner et al., 2012; Duarte et al., 2014](#)). In this regard, the emissions estimated in the CGE model for the year t , E_t , take into account both household direct emissions, E_t^{DH} , and emissions from production activities, E_t^{PA} .

$$E_t = E_t^{\text{DH}} + E_t^{\text{PA}} \quad (1)$$

E_t^{DH} emissions are obtained as the product of a given vector \mathbf{i} of emissions per unit of each type of energy (“Coal”, “Refined oil” and “Gas”) by the household energy consumption vector \mathbf{c} . E_t^{PA} emissions are calculated using the input-output model (see [Sánchez-Chóliz et al., 2007](#)).

$$E_t^{\text{PA}} = \mathbf{d}'(\mathbf{I} - \mathbf{A}_t)^{-1}\mathbf{s}_t \quad (2)$$

Where \mathbf{d} is a given vector of productive emissions intensities (kt of $\text{CO}_{2\text{eq}}$ and SO_x per monetary unit of output); $(\mathbf{I} - \mathbf{A}_t)^{-1}$ is the Leontief inverse matrix, and \mathbf{s}_t is the vector of final demand. Bear in mind that, for each period t , the CGE model characteristics, the incorporated improvements, and the new equilibrium at t define the inverse matrix, $(\mathbf{I} - \mathbf{A}_t)^{-1}$ and final demand, \mathbf{s}_t .

In our analysis, we consider two types of emissions, greenhouse gases (GHG) and sulphur oxide (SO_x). The greenhouse gases comprise carbon dioxide (CO_2), methane (CH_4), nitrogen monoxide (N_2O), sulphur hexafluoride (SF_6), hydrofluorocarbons, and perfluorocarbons. GHG emissions are expressed in kilotons of equivalent carbon dioxide (kt of $\text{CO}_{2\text{eq}}$), using the Global Warming Potential published in [IPCC \(2007\)](#). Primary information on emissions has been obtained from the Emissions satellite accounts provided by the Spanish National Statistics Institute ([INE, 2005b](#)).

4. Scenarios and results

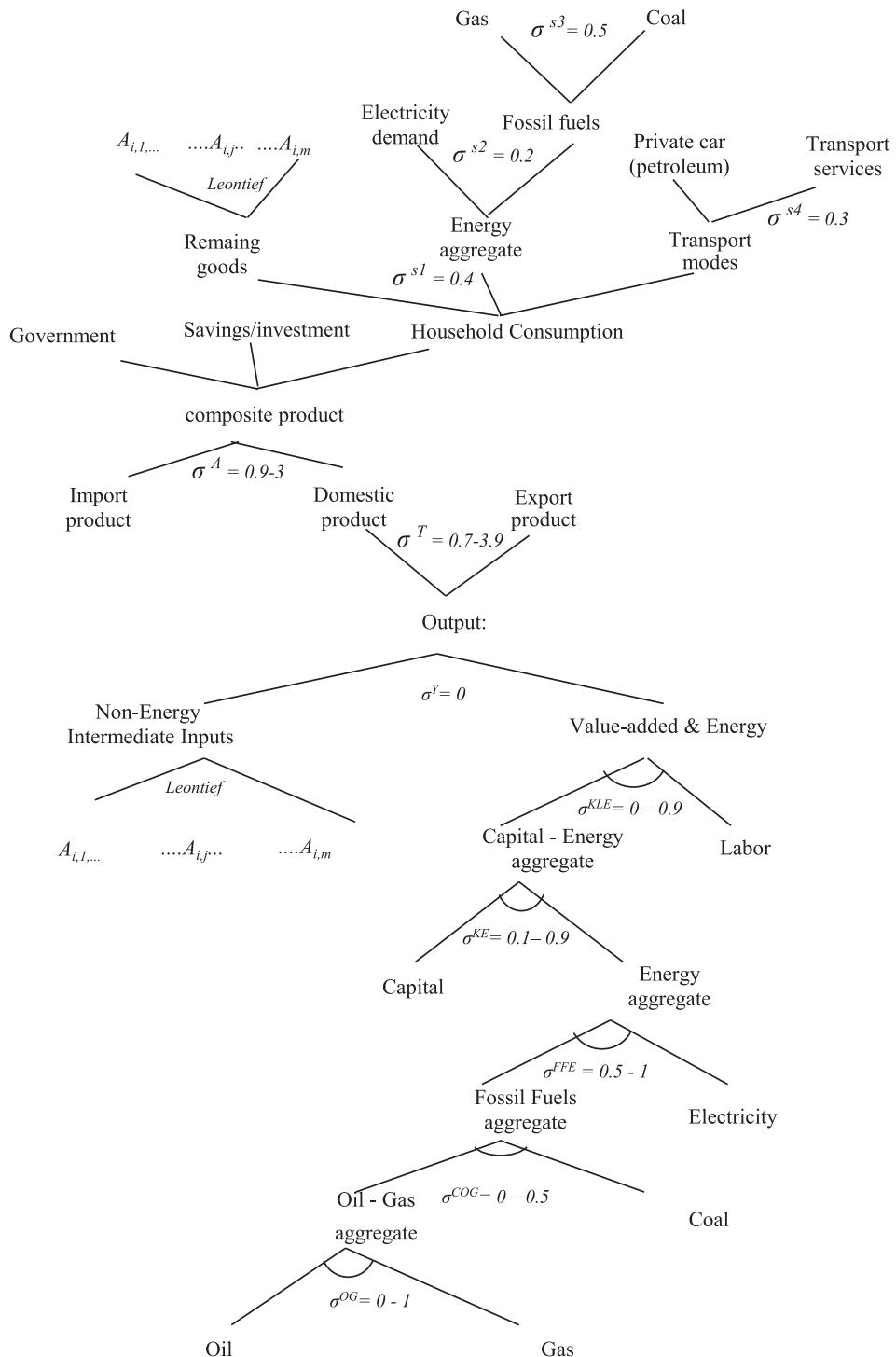
Once we have designed and calibrated the dynamic CGE model, we proceed to simulate and evaluate alternative changes in the structure of private consumption through technological improvements, for the period 2005–2030. These changes provoke other changes in the current prices of goods and services, and in the behaviour of economic agents at any time t , defining a new final equilibrium. We quantify their impacts and their evolution by comparing each new equilibrium with a reference path, which is imposed by the parameters of the dynamic model (growth and interest rates).

4.1. Reference path and its initial values for 2005

The reference path used for evaluating the impacts of energy

³ Note that these values are the average values from 2005 to 2015 and allow us to isolate our results from growth and recession periods.

⁴ This function is included in the model, following [Philip et al. \(2014\)](#). Similar results could be expected using other types of logistic functions (see [Naseri and Elliott, 2013](#)).

**Fig. 1.** Structure of the dynamic model.

Source: Own elaboration.

efficiency improvements is obtained from running the CGE model defined in the previous section (see [Appendix A of the SI](#)), without including changes in the structure of consumption patterns. In other words, it is the expected evolution if no environmental policy is implemented from 2005 to 2030.

The levels of direct emissions and emissions from production activities in 2005, the base year, are presented in [Table 1](#). We also show the evolution of emissions along the reference path, assuming that the vector of emission coefficients (kt of CO₂eq per monetary unit of output)

does not vary. Economic activities in 2005 account for 83.79% of total GHG and 98.58% of total SO_x emissions. In these activities, emissions associated with household consumption are the most significant; 189,903 kt of CO₂eq and 668 kt of SO_x. Clearly, household indirect emissions far outweigh their direct emissions.

Emissions from “Electricity”, “Agriculture, forestry and aquaculture”, “Non-metallic and mineral products”, “Transport services” and “Refined petroleum products” comprise mainly GHG and SO_x emissions (see [Table B1 of Appendix B of the SI](#)). Specifically, the

Table 1

Spanish GHG and SO_x emissions in the reference path (2005, 2010, 2020 and 2030).
Source: Own elaboration.

| | 2005 | | | | 2010 | | 2020 | | 2030 | |
|--|----------------|---------------|----------------------|---------------|----------------|----------------------|----------------|----------------------|----------------|----------------------|
| | GHG (kt) | % | SO _x (kt) | % | GHG (kt) | SO _x (kt) | GHG (kt) | SO _x (kt) | GHG (kt) | SO _x (kt) |
| Household direct emissions (1) | 81,827 | 16.21 | 19 | 1.42 | 85,026 | 20 | 91,805 | 21 | 99,124 | 23 |
| Emissions from production activities (2) | 422,988 | 83.79 | 1300 | 98.58 | 439,526 | 1351 | 474,567 | 1458 | 512,401 | 1575 |
| <i>Households</i> | 189,903 | 37.62 | 668 | 50.66 | 197,328 | 694 | 213,059 | 750 | 230,045 | 810 |
| <i>Export</i> | 84,585 | 16.76 | 255 | 19.34 | 87,892 | 265 | 94,899 | 13 | 102,465 | 309 |
| <i>Government</i> | 61,821 | 12.25 | 129 | 9.78 | 64,238 | 134 | 69,360 | 145 | 74,889 | 157 |
| <i>NPISH</i> | 3477 | 0.69 | 6 | 0.46 | 3613 | 7 | 3901 | 7 | 4212 | 8 |
| <i>Investment</i> | 83,202 | 16.48 | 240 | 18.20 | 86,455 | 250 | 93,347 | 270 | 100,789 | 291 |
| Total emissions (1 + 2) | 504,816 | 100.00 | 1319 | 100.00 | 524,553 | 1370 | 566,372 | 1479 | 611,525 | 1597 |

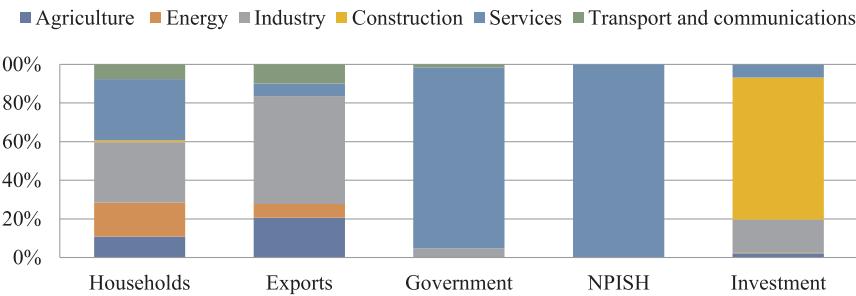


Fig. 2. Structure of total GHG emissions associated with 2005 Spanish final demand (%).
Source: Own elaboration.

electricity sector accounts for 101,355 kt of CO_{2eq}, representing 20.08% of GHG emissions, and 848,051 kt of SO_x, representing 64.31% of SO_x emissions. Meanwhile, emissions associated with transport use, such as “Refined petroleum products” and “Transport services”, account for 55,034 kt of CO_{2eq}, representing 10.09% of GHG emissions, and 171,393 kt of SO_x, representing 12.99% of SO_x emissions. Therefore, changes in both electricity and transport use by households may have a significant impact in terms of emissions, changing the initial trends.

The productive pollution structure of each component of Spanish final demand by product group in 2005 is shown in Figs. 2 and 3. In Fig. 2, it is clear that GHG emissions associated with household consumption are mainly due to the “Energy”, “Industry”, and “Services” sectors, while “Agriculture” and “Industry” represent a significantly larger share of emissions attributable to exports. By contrast, Government and Non-Profit Institutions Serving Households (NPISH) emissions are explained by the consumption of services (education and health), and those associated with investment arise primarily from “Construction”.

We can see in Fig. 3 that SO_x emissions have a very different structure for private consumption and exports, and a greater share of their emissions are associated with the “Energy” sector, while the SO_x emissions for the rest of final demand present a pattern similar to that of GHG emissions.

4.2. Description of scenarios

Fig. 4 shows the current evolution of efficiency from the energy intensities in households for electricity and petroleum use, from 2005 to 2015. In this figure, we can see the final consumption of electricity and petroleum in households in Spain (IDAE, 2005–2015) per unit of final consumption expenditure in constant prices (Eurostat, 2005–2015), taking the value in 2005 as 100. These evolutions show that efficiency from electricity intensity in households has slightly decreased from 2005 to 2015, while efficiency from petroleum intensity presents a considerable increment from 2005, above 30%. Then, the 20% reduction in total energy consumption by 2030 will not be easy to achieve, and will likely require an aggressive policy.

In line with the objectives stated above, we simulate the following scenarios⁵ for the period 2005–2030:

- **Scenario 1, called “ELE”:** We represent electricity savings in the domestic sector, achieved through a continuous improvement in household energy-use efficiency. This simulation emulates the impact of the replacement of obsolete or low-efficiency domestic devices by appliances labelled Class A or higher, turning down air-conditioning or lighting, not leaving appliances on stand-by, using energy-saving light bulbs, etc. Note that these improvements are strongly associated with learning processes, which we assume evolve following logistic patterns. This improvement is designed to achieve a net reduction in electricity use of 20%⁶ by 2030, following the Energy Efficiency Action Plan of Spain (NEEAP, 2014–2020). We thus expect a fall in GHG emissions associated with this electricity consumption of around 20%.⁷
- **Scenario 2, called “TRN”:** We simulate a change in the transportation mode of citizens through the use of efficient vehicles that require less fuel. This scenario again models a logistic improvement in efficiency in household fuel use, with the ultimate objective of improving mobility by fostering more efficient modes of transport. The technological improvement occurs as a reduction in the household consumption of Petroleum products, impacting on the economy as household saving and lower demand for these products. This is again designed to get a net fall of 20% in petroleum use by 2030, pending a similar reduction in the associated emissions.

⁵ Actions included in these scenarios are reported by European citizens as the most common energy-related actions carried out for environmental reasons (Eurobarometer, 2008). In fact, 47% of European citizens in the survey reported one or more of the actions in Scenario 1 to reduce energy consumption, and 28% reported one or more of the actions in Scenario 2.

⁶ Note that this 20% net reduction is the final reduction after the simulation has taken into account direct, indirect, and rebound effects.

⁷ We simulate improvements in electricity household use because electricity is still the only source used in household appliances, air conditioning, and lighting in Spanish households (IDAE, 2010). It allows us to isolate impacts from improvements in other energy sources.

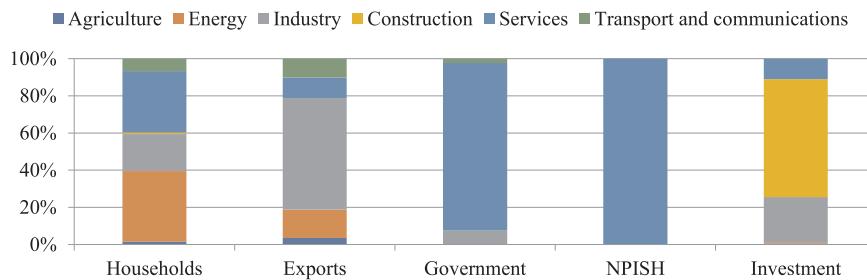


Fig. 3. 2005 Structure of total SO_x emissions associated with 2005 Spanish final demand (%).

Source: Own elaboration.

- **Scenario 3, called “ELE + TRN”:** This scenario evaluates improvements included in Scenarios 1 and 2 simultaneously. Thus, we could expect a greater decline in GHG emissions, close to the sum of the falls from Scenario 1 and 2, and as an approximation to the target of 40% by 2030.

The scenarios proposed simulate changes to be implemented through the routine replacement of appliances and vehicles by other more efficient units, with the implication that no costs are included. This allows us to isolate the effects of technological improvements on the use of energy. However, these results can be affected, in practice, by the costs associated with these transformations. In this regard, an approximation to potential impacts involving costs is explored in Appendix B of the SI following IDAE 2011–2020 (IDAE, 2011).

4.3. Results of scenario simulations

4.3.1. Technological improvement evolution

As noted, the generalization of the implementation of improvements among citizens from 2005 to 2030, in our model, follows a logistic (Gompertz) evolution. The growth of improvement is continuous, slow in the early years, close to 2005, with an intermediate acceleration and a smooth growth following a certain number of periods. Fig. 5 shows the evolution of the level of efficiency of technology assumed in each scenario, from 2005 to 2030, compared to the 2005 level. These curves are estimated following a logistic evolution, which are captured through Gompertz functions presented in Eq. (A33) in Appendix A of the SI. The estimated parameters of each function attempt to capture the real evolution from 2005 to 2015 described in Fig. 4.

In Fig. 5, we observe that an improvement of efficiency by 2030 of around 80% (compared to 2005) is required to reduce the final household energy consumption of each type of energy studied (electricity and fuel in Scenarios 1 and 2, respectively) by 20%. In other words, we cut by almost a half the energy used in 2005. These new levels of efficiency mean that very efficient devices (both for electricity and fuel use) are available among more citizens to achieve the same output.

The efforts to achieve the targeted reduction in the electricity sector (Scenario 1) are greater than in the fuel sector (Scenario 2), which clearly improved from 2008 and so is in line with the evolution observed in Fig. 4, where we have improvements in petroleum intensity from the first period, and an average level around 32% in 2015. By contrast, in the case of electricity, the efficiency improvement is very close to zero up to 2015, and always remains smaller than for petroleum.

4.3.2. Simulation results

The following tables, Tables 2 (energy results) and 3 (macroeconomic results), show the effects of these gradual technological improvements in the electricity and transport sectors for the three scenarios considered. We also present the results as percentage changes in the use of energy with respect to the reference path and, for some of them, also as percentage changes compared to 2005.

In Table 2, we can see that the improvements in household efficiency electricity use (Scenario 1) provoke a 20.05% saving in household electricity consumption by 2030 compared to 2005, and a saving of 34% compared to the 2030 level in the reference path (the expected evolution without environmental policies). This last percentage is higher because of the growth, and the associated use of energy, from 2005 to 2030 incorporated in the reference path. These reductions involve a small expansionary increase in non-electrical goods, which in turn increases total private consumption by 0.47% (Table 3), as a consequence of household income savings and the substitution and income effects. The incentive in non-electrical goods entails increases in the consumption of the remaining energy uses (coal, gas and fuel) and in the remaining non-energy goods. This stimulus in non-electrical goods thus involves an increase of electricity demand by industry of 2.27%. However, this stimulus is offset by the reduction in household electricity consumption, and total electricity use declines by 4.69%. A fall in electricity generation of 4.23% is observed as less electricity is required, along with a fall in the price of power (5.50%). Electricity imports are reduced, while electricity exports are increased as a consequence of falling electricity prices, reflecting positive competitiveness

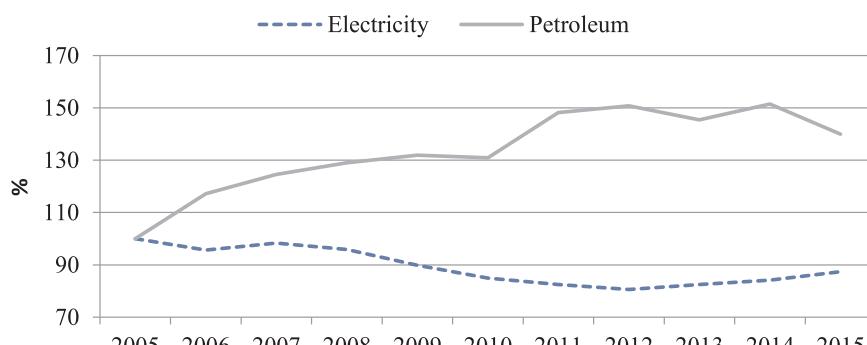


Fig. 4. Intensity level in household energy use in Spain; 2005 level = 100.

Source: Own elaboration based on IDAE (2005–2015) and Eurostat (2005–2015).

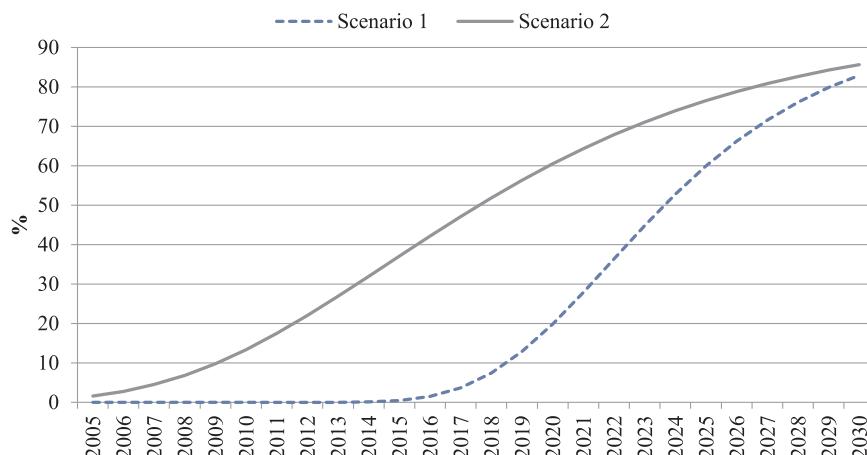


Fig. 5. % Level of efficiency improvements.

Source: Own elaboration

effects. Regarding the total use in the economy (industry and households) of coal, fuel, electricity, and gas, total energy use falls by 2.58%, with a reduction in household energy use of 12.92%.

In Table 2, we can also see the results for 2010 and 2020. For the latter, we can repeat the previous comments, although the figures (percentage changes) are smaller because the logistics of improvements have only partially evolved.

Similar sectoral results for the period 2005–2030 are observed in Scenario 2, with more efficient modes of transport. The fuel consumption in 2030 reaches the net reduction of 20.08% compared to 2005, and 34.74% compared to the reference path (that is, the situation in 2030 with no policy), while the price and production of fuel also fall. This reduction in household fuel use stimulates the consumption of non-fuel goods with a corresponding expansionary impact on the economy, and total private consumption increases by 0.52% (Table 3). Note that, despite this stimulus, by contrast with Scenario 1, fuel demand by industries is reduced by 1.18% as fuel is mainly used by the transport sectors, unlike electricity that is also used in all sectors as a significant intermediate input. The impact in the remaining energy products by households (coal, gas and electricity) is lower than with the improvements in efficiency in electricity household use, as expected, due to the use of energy in the activity simulated being completely different. However, the stimulus in the economy because of a larger demand of non-fuel goods and services is also observed.

As in the case of the electricity sector, total energy use falls by 3.32% in all energy sectors and in both industrial and household use, which means a reduction of the global energy use in the economy. Note that when we explore the evolution from 2010 to 2030 in Scenario 2, results are closer, due to the shape of the logistic evolution that represents a faster growth in the first half of the period and a smooth growth in the second half. For the same reason, the relative differences between 2010 and 2020 are now greater than in Scenario 1.

Table 2 also presents the energy results of Scenario 3 that include both technological improvements. As expected, reductions by 2030 for total household energy use (30.55%) and energy demand by industries (1.37%) are approximately the sum of those of Scenarios 1 and 2. Note also the importance of the improvements incorporated by households for the total economy, which are 5.93% of total energy use. We also see that household electricity and fuel uses are reduced to a lesser extent than in Scenarios 1 and 2, due to the rebound effect of both simultaneous improvements.

We can also see in Table 3 the macroeconomic results of all scenarios, with the figures of Scenario 3 being close to the sum of figures from Scenarios 1 and 2. In summary, the improvements in household energy use stimulate total production from the economy as a whole, driven by the stimulus in non-electrical goods consumption (Scenario 1)

and non-fuel goods consumption (Scenario 2). The consumer price index decreases in the three scenarios in any given year, fostered by reductions in all energy prices that outweigh increases in non-energy prices. Moreover, we can also observe positive impacts on employment, capital investment, and private consumption. In the three scenarios, real wages rise. This stimulus in the economy is driven by savings by households in energy goods that stimulate demand.

Specifically, and as we have seen in the results, technological improvements generate savings, in our case savings by households that are then devoted to new consumption and investment. Both pathways generate more activity and may reduce, and even eliminate, the environmentally-positive effects of the improvements, which are usually known as rebound effects. Although these effects are not always taken into account, their importance is generally great and should not be overlooked.

For a better understanding of these impacts on our process of energy-use reduction, Table 4 shows a quantification of the rebound effect in the Spanish economy based on the formulation provided by Lecca et al. (2014).⁸ We estimate the rebound effects of the lower use of electricity and fuel in households, and also of the total energy use in the whole economy. When we observe the economy-wide rebound effects in electricity use in Scenario 1, we see a substantial rebound of 70.52% by 2030, which has considerable significance; more than two-thirds of direct reduction is offset by the rebound effect. Similarly, the economy-wide rebound effects in fuel use in Scenario 2 achieve a level of 51.01% by 2030, smaller than the electricity rebound effect due to the higher concentration (in comparison with electricity) of demand for fuel by industry, already observed in Table 2. As we would expect, rebound effects in Scenario 3 present a percentage intermediate between Scenario 1 and 2 of the rebound effect in electricity and fuel use at the sector level, as they take into account two efficiency improvements simultaneously. In this Table, we can also see these effects increase over time, going from 50.19% in 2010 in Scenario 1 to 58.15% and 70.52% in 2020 and 2030, respectively. Similarly, the rebound effects in Scenario 2 change from 25.29% in 2010, to 44.45% in 2020, and 51.01% in 2030. The tempo of the change mainly depends on the types of logistic evolving as shown in Fig. 5. In Table 4, we can also see the total economy-wide rebound effects in all energy usage of each scenario; in Scenario 1, these effects are smaller than the previous effects, and they

⁸ As the authors explain, the formulation is a “measure of the difference between the proportionate change in the actual energy use and the proportionate change in energy efficiency. An increase in efficiency in energy use reduces the price of energy in that use. This reduction leads consumers to substitute energy for other goods and services, implying that the proportionate reduction in energy use is typically less than the proportionate improvement in energy efficiency”.

Table 2
Energy results (% change with respect to the reference path in 2010, 2020, and 2030).

| | Scenario 1: ELE | | | Scenario 2: TRN | | | Scenario 3: ELE+TRN | | |
|-------------------------------------|---|--|---|--|---|---|--|--|--|
| | 2010 | 2020 | 2030 | 2010 | 2020 | 2030 | 2010 | 2020 | 2030 |
| Household electricity consumption | % to 2005 % to the reference path | 3.91 0.00 | -0.81 -11.59 | -20.05 -34.00 | Household fuel consumption | % to 2005 % to the reference path | -3.64 -8.26 | -18.01 -27.83 | -20.08 -34.74 |
| Other household consumption results | Coal consumption Gas consumption Fuel consumption Non-energy goods Electricity production | 0.00 0.00 0.00 0.00 0.00 | 1.73 1.94 0.19 0.09 -1.43 | 5.58 6.17 0.54 0.26 -4.23 | Coal consumption Gas consumption Electricity consumption Non-energy goods Fuel sector results | 0.11 0.13 0.12 0.07 -0.58 | 0.39 0.47 0.44 0.25 -1.96 | 0.49 0.33 0.56 0.33 -2.44 | Coal consumption Gas consumption Non-energy goods Household fuel consumption |
| Sector results | Electricity imports Electricity exports Electricity demand by industry Total electricity use Total household energy use Energy use | 0.00 0.00 0.00 0.00 0.00 0.00 | -6.81 -1.93 2.27 -1.60 -4.41 -0.24 | -18.64 -5.50 -4.69 -4.69 -12.92 -0.66 | Fuel imports Fuel exports Fuel demand by industry Total fuel use Energy demand by industry | -0.15 0.22 -0.28 -1.40 -4.16 -0.16 | -0.53 0.76 -0.94 -4.72 -14.01 -0.55 | -0.66 0.99 -1.18 -5.89 -17.49 -0.69 | Main sector results Electricity demand by industry Total electricity use Fuel demand by industry Total fuel use Energy demand by industry |
| Total energy use | | 0.00 | -0.89 | -2.58 | Total energy use | -0.79 | -2.66 | -3.32 | Total energy use |

are around two-thirds of electricity effects, in accordance with the weight of household electricity use in total energy. The contrary is observed in Scenario 2, due to the importance of the weight of household fuel use in total energy use, as noted earlier. Rebound effects are larger for total energy use in the economy in Scenario 3, as the improvement in efficiency achieved from household electricity and fuel use is insufficient, and larger efforts from industry sectors would be required to achieve a greater decline in total energy use.

Tables 5, 6 present the effects from 2005 to 2030 on emissions. The higher household energy use efficiency (Scenario 1) leads to a total reduction of 0.66% in GHG emissions by 2030 and 2.89% in SO_x emissions, representing a cut of 4048 kt of CO_{2eq} and 46.15 kt of SO_x (see Table 6). These small declines are due to the increase of 1.30% in emissions from household direct emissions, as a consequence of the rebound effects triggered by electricity savings, which increase the consumption of coal, gas, and refined petroleum products.⁹ Thus, reductions in total emissions are smaller due to reductions in emissions from production activities. Reductions in SO_x emissions are greater than GHG emissions in Scenario 1, due to SO_x emissions associated with the electricity sector representing a larger share of the total of SO_x emissions, than GHG emissions of its total (see Table B1 of Appendix B of the SI; 64.31% of SO_x emissions versus 20.08% of GHG emissions). As expected, the environmental effects grow year by year, reaching the highest values in 2030.

Regarding environmental impacts, technological improvements in sectors linked to transport services (Scenario 2) lead to a total reduction of 4.90% in GHG emissions by 2030, and 0.57% in SO_x emissions, representing 29,989 kt of CO_{2eq} and 9.18 kt of SO_x, respectively (see Table 6).

Thus, Scenario 3, which captures the combined effect of both Scenarios 1 and 2, presents a total reduction of 5.59% in GHG emissions by 2030 compared to the reference path, and 3.49% in SO_x emissions. This same reduction for 2010 is 1.17% and 0.14% respectively. This scenario shows declines, as does Scenario 2, in emissions from production activities, while showing reductions, as in Scenario 1, in household direct emissions.

To sum up, achieving global technological improvements through more efficient domestic devices, together with improvements in transportation, would reduce total GHG and SO_x emissions year by year, as expected, and would help to satisfy the Spanish strategy for year 2030. However, the positive effects of these types of improvement are limited, primarily because the major direct emitters are production activities, and so additional measures on behalf of Spanish productive technologies are required to achieve a greater reduction in emissions and to achieve international targets.

To shed more light on the importance of rebound effects, Table 6 disaggregates the 2030 results by main accounts, and shows that improvements in the electricity sector (Scenario 1) lead to reductions in total emissions (GHG and SO_x), largely due to reductions in emissions from production activity, specifically in household indirect emissions associated with electricity consumption (10,723 kt of CO_{2eq} and 86.57 kt of SO_x), and not from household direct emissions. The improvements via household savings provoke a rebound effect in Fuel and Other products and services, causing increases both in household indirect emissions and in household direct emissions, due to increased consumption of coal, gas, and refined petroleum products (1293 kt of CO_{2eq} and 0.30 kt of SO_x). Finally, the rebound effects associated with government arise from the consumption of services (education and health), and those associated with investment come mostly from the construction sector.

In the case of Scenario 2, with improvements in transport sectors,

⁹ The overall change in GHG and SO₂ emissions is the same, since it is measured as a percentage change with respect to the baseline scenario. These variations depend on the elasticities of substitution in the consumption function. Note that the amount of emissions variations is different; see Table 6.

Table 3

Macroeconomic results (% change with respect to the reference path in 2010, 2020 and 2030).
Source: Own elaboration.

| | Scenario 1: ELE | | | Scenario 2: TRN | | | Scenario 3: ELE + TRN | | |
|---------------------|-----------------|--------|--------|-----------------|--------|--------|-----------------------|--------|--------|
| | 2010 | 2020 | 2030 | 2010 | 2020 | 2030 | 2010 | 2020 | 2030 |
| Production | 0.00 | 0.03 | 0.07 | 0.00 | 0.01 | 0.01 | 0.00 | 0.04 | 0.08 |
| Imports | 0.00 | − 0.23 | − 0.65 | 0.04 | 0.14 | 0.13 | 0.04 | − 0.09 | − 0.52 |
| Exports | 0.00 | 0.18 | 0.56 | 0.00 | 0.01 | 0.04 | 0.00 | 0.19 | 0.61 |
| Private consumption | 0.00 | 0.16 | 0.47 | 0.12 | 0.41 | 0.52 | 0.12 | 0.57 | 0.98 |
| Capital investment | 0.00 | 0.14 | 0.40 | 0.07 | 0.24 | 0.29 | 0.07 | 0.38 | 0.69 |
| Unemployment | 0.00 | 0.00 | − 1.18 | − 0.10 | 0.00 | − 0.54 | − 0.10 | 0.00 | − 1.70 |
| Nominal wages | 0.00 | 0.00 | − 0.02 | − 0.05 | − 0.17 | − 0.26 | − 0.05 | − 0.16 | − 0.28 |
| CPI | 0.00 | − 0.02 | − 0.11 | − 0.05 | − 0.19 | − 0.30 | − 0.05 | − 0.21 | − 0.39 |

reductions in total emissions (GHG and SO_x) come primarily from household direct emissions (unlike in Scenario 1), as a consequence of reductions in the consumption of refined petroleum products (29,423 kt of CO_{2eq} and 6.75 kt of SO_x). However, rebound effects partially offset the previous declines. We can see some additional emissions associated with the production activities. The largest positive component of these indirect emissions corresponds to additional household consumption of electricity and remaining products and services. By contrast, the indirect emissions from production activity associated with fuel consumption are reduced.

When we look at per capita results, Table 7 presents an approximation of impacts per capita by 2030, compared with 2005 without technological improvements. The data on population growth are obtained from Spanish statistics (INE, 2005–2015a, 2005–2015b), following the current trend through to 2030. Improvements in household energy use in Scenario 3 could lead to emissions as low as 5.60 GHG tonnes per capita, significantly lower than the 6.28 t per capita emissions if no improvements are implemented. These numbers include direct and indirect emissions of household consumption. Significant reductions are shown in the case of both improvements in electricity and fuel consumption (Scenario 3), with reductions in GHG emissions per capita greater than 10%.

Finally, as noted earlier, these positive outcomes can be influenced by the assumption of zero cost associated with technological improvements. Despite that our objective is to study the impacts of these improvements in energy use, we also explore the potential impacts of including payment costs in Table B2 in Appendix B of the SI. Our findings show negative impacts in the economy (production, employment, consumption, trade, prices) in 2010 and 2020, due to the payment of these costs that could shrink consumption. However, positive results could reach the economy in 2030, once payment costs are offset with savings arising from the technological efficiency, as reductions in household energy use are larger. Note that larger reductions in household energy use would involve smaller economy-wide rebound effects, in comparison with results shown in Table 4.

Table 4

Economy-wide rebound effects (%).
Source: Own elaboration.

| $R = \left[1 + \frac{\dot{E}}{\alpha \gamma} \right] 100$ | Scenario 1: ELE | | | Scenario 2: TRN | | | Scenario 3: ELE + TRN | | |
|---|-----------------|--------------|--------------|-----------------|--------------|--------------|-----------------------|--------------|--------------|
| | 2010 | 2020 | 2030 | 2010 | 2020 | 2030 | 2010 | 2020 | 2030 |
| Technical energy-efficiency improvement (γ) | 0.00 | 0.20 | 0.83 | 0.13 | 0.61 | 0.86 | 0.13 | 0.80 | 1.69 |
| Change in total electricity or fuel use (\dot{E}) | 0.00 | − 0.02 | − 0.05 | − 0.01 | − 0.05 | − 0.06 | − 0.01 | − 0.07 | − 0.12 |
| Share (Household electricity or fuel use/Total use of electricity or fuel) (α) | 0.19 | 0.19 | 0.19 | 0.14 | 0.14 | 0.14 | 0.16 | 0.16 | 0.16 |
| Total economy-wide rebound in electricity or fuel use (%) | 50.19 | 58.15 | 70.52 | 25.29 | 44.45 | 51.01 | 34.65 | 47.38 | 55.85 |
| Change in total energy use (\dot{E}) | 0.00 | − 0.01 | − 0.03 | − 0.01 | − 0.03 | − 0.03 | − 0.01 | − 0.04 | − 0.06 |
| Initial share (Household electricity or fuel use/Total energy use) (α) | 0.06 | 0.06 | 0.06 | 0.08 | 0.08 | 0.08 | 0.14 | 0.14 | 0.14 |
| Total economy-wide rebound in all energy use (%) | 12.05 | 29.00 | 50.70 | 26.07 | 45.03 | 51.48 | 58.68 | 69.05 | 75.39 |

5. Sensitivity analysis

The results of a modelling process can be affected by various sources of uncertainty (Lenzen et al., 2003), so for a robustness test we conduct a sensitivity analysis of some specific features of the model used. Studies using CGE models usually check the sensitivity of the alternative elasticity of substitutions, so we conduct a sensitivity analysis for Scenario 1 on the elasticity of substitution between electricity and the fossil fuels aggregate in the consumption function. Specifically, we increase and then reduce the initial value. We then conduct another sensitivity analysis for Scenario 2 on the elasticities that affect the transport services sectors. In this case, we again increase and then reduce the initial values. As a first conclusion, the main results of the analysis are robust to the different specifications. Nevertheless, the values of elasticities influence the strength of the substitution effect, due to changes in the relative prices of the alternatives. The results can be seen in Table 8, where the first columns are figures obtained in the simulations shown previously.

In both scenarios, a lower value of elasticity involves a greater reduction of household electricity or fuel consumption in each scenario. This larger decline offsets a higher relative demand by the rest of industry, due to the lack of substitutes, and thus the total use of electricity is also lower. In contrast, a higher value of elasticity leads to a lesser reduction of electricity or fuel consumption as a consequence of a greater flexibility to substitute with other sectors. However, when we observe the combination with the rest of the energy sectors, a higher value of elasticity implies a lower total energy use, due to the greater flexibility in using the more appropriate energy sector. Comparing both sectors, lesser differences in results in the electricity sector reveal an increased rigidity of the electricity sector caused by a greater need for this good. In other words, the use of transport is more sensitive to changes in flexibility and substitutability, suggesting that policy strategies focused on transportation could have more significant impacts in the use of energy.

Table 5

Environmental results in 2010, 2020 and 2030 (% change with respect to the reference path).

Source: Own elaboration.

| Emissions results | Scenario 1: ELE | | | Scenario 2: TRN | | | Scenario 3: ELE + TRN | | |
|---|-----------------|---------------|---------------|-----------------|---------------|---------------|-----------------------|---------------|---------------|
| | 2010 | 2020 | 2030 | 2010 | 2020 | 2030 | 2010 | 2020 | 2030 |
| Emissions of production activities (GHG) | 0.00 | − 0.24 | − 1.04 | − 0.03 | 0.26 | − 0.13 | − 0.03 | − 0.10 | − 1.18 |
| Emissions of production activities (SO _x) | 0.00 | − 0.68 | − 2.95 | − 0.04 | 0.89 | − 0.16 | − 0.04 | − 0.13 | − 3.13 |
| Household direct emissions (GHG) | 0.00 | 2.52 | 1.30 | − 7.04 | − 24.04 | − 29.61 | − 7.04 | − 23.66 | − 28.44 |
| Household direct emissions (SO _x) | 0.00 | 2.52 | 1.30 | − 7.04 | − 24.04 | − 29.61 | − 7.04 | − 23.66 | − 28.44 |
| Total emissions (GHG) | 0.00 | 0.21 | − 0.66 | − 1.17 | − 3.71 | − 4.90 | − 1.17 | − 3.94 | − 5.59 |
| Total emissions (SO_x) | 0.00 | − 0.64 | − 2.89 | − 0.14 | 0.53 | − 0.57 | − 0.14 | − 0.47 | − 3.49 |

Table 6

Changes in atmospheric emissions in 2030.

Source: Own elaboration.

| | GHG (kt) | | | SO _x (kt) | | |
|--|---------------|-----------------|-----------------|----------------------|---------------|-----------------|
| | Sce1: ELE | Sce2: TRN | Sce3: ELE + TRN | Sce1: ELE | Sce2: TRN | Sce3: ELE + TRN |
| Household direct emissions (1) | 1293 | − 29,346 | − 28,190 | 0.30 | − 6.74 | − 6.47 |
| Coal | 21 | 1 | 22 | 0.00 | 0.00 | 0.01 |
| Refined petroleum products | 405 | − 29,423 | − 29,160 | 0.09 | − 6.75 | − 6.69 |
| Gas | 867 | 75 | 947 | 0.20 | 0.02 | 0.22 |
| Emissions from production activity (2) | − 5341 | − 642 | − 6024 | − 46.45 | − 2.45 | − 49.23 |
| Households | − 8392 | − 1066 | − 9397 | − 70.18 | − 7.42 | − 77.11 |
| Electricity | − 10,723 | 155 | − 10,620 | − 86.57 | 1.23 | − 85.76 |
| Fuel | 35 | − 1744 | − 1688 | 0.21 | − 9.96 | − 9.64 |
| Other products and services | 2296 | 524 | 2912 | 16.18 | 1.31 | 18.29 |
| Export | 1090 | − 1 | 1170 | 8.72 | 0.23 | 9.48 |
| Government | 513 | − 19 | 517 | 4.32 | − 0.20 | 4.27 |
| NPISH | − 158 | − 654 | − 799 | − 0.13 | − 1.22 | − 1.22 |
| Investment | 1606 | 1098 | 2485 | 10.81 | 6.17 | 15.35 |
| Total emissions (1 + 2) | − 4048 | − 29,989 | − 34,214 | − 46.15 | − 9.18 | − 55.70 |

6. Conclusions

This paper examines the impact of adopting demand-side environmental strategies for atmospheric emissions in the Spanish economy. Focusing on household consumption, we assume that Spanish households continuously reduce their electricity and fuel use, gradually increasing the efficiency levels each year, and we analyse the environmental impact of these improvements. To achieve this objective, a dynamic Computable General Equilibrium (CGE) model is calibrated for the Spanish economy using data from the period 2005–2015, which allows us to evaluate the continuous and increasing effects throughout the period 2005–2030. The changes in household consumption patterns are implemented via logistic evolutions to capture the transition toward certain 2030 targets, in line with Spain's Energy Efficiency Action Plan.

The data for the Spanish economy for the initial year, 2005, suggest that both SO_x and GHG emissions are concentrated in a very few economic activities, in particular the energy sectors and agriculture, accounting for production activity of more than 80% of GHG and SO_x

emissions. Indeed, emissions (embodied emissions) associated with households and exports are the most significant. This is our starting point and, in line with targets, we compare our results to this year.

We have simulated two measures established in the Energy Efficiency Action Plan for Spain, which are directly related to changes in household consumption through technological improvements in household electricity use (Scenario 1), and via more efficient modes of transport (Scenario 2). Additionally, both measures are analysed simultaneously (Scenario 3). The available data allow us to design two possible logistic evolutions for these scenarios, looking for a net reduction by 2030 in scenarios 1 and 2 of around 20% over 2005 levels of electricity and fuel household consumption, respectively. These are in line with the 40% reduction in energy consumption fixed by the EU for 2030 in the total economy.

The simulated changes achieve the environmental goals set out in the Spanish strategy. However, results also show that this achievement would involve radical changes for consumers, and their implementation would not be easy. We can confirm this claim looking at Fig. 5, where

Table 7

Household total emissions per capita in 2030 compared to 2005.

Source: Own elaboration.

| | Tn/per capita | Tn/per capita | | | % change to 2005 | | |
|----------|-----------------|---------------|-------------|-----------------|------------------|---------------|-----------------|
| | | Sce1: ELE | Sce2: TRN | Sce3: ELE + TRN | Sce1: ELE | Sce2: TRN | Sce3: ELE + TRN |
| Direct | GHG | 1.89 | 1.93 | 1.34 | 1.36 | 1.95 | − 29.15 |
| | SO _x | 0.00 | 0.00 | 0.00 | 0.00 | 1.95 | − 29.15 |
| Indirect | GHG | 4.39 | 4.25 | 4.39 | 4.23 | − 3.03 | 0.17 |
| | SO _x | 0.02 | 0.01 | 0.02 | 0.01 | − 8.08 | − 0.28 |
| Total | GHG | 6.28 | 6.18 | 5.73 | 5.60 | − 1.53 | − 8.66 |
| | SO _x | 0.02 | 0.01 | 0.02 | 0.01 | − 7.81 | − 1.07 |

Table 8

Sensitivity analysis of elasticities values in 2030 (% change compared with reference path).

Source: Own elaboration.

| | $\sigma^{s2} = 0.2$ (see Fig. 1) | $\sigma^{s2} = 0$ | $\sigma^{s2} = 0.4$ |
|-----------------------------------|----------------------------------|-------------------|---------------------|
| Household electricity consumption | –34.00 | –36.01 | –32.21 |
| Electricity demand by industry | 2.27 | 2.37 | 2.18 |
| Total electricity use | –4.69 | –5.00 | –4.42 |
| Total household energy use | –12.92 | –12.78 | –13.05 |
| Energy demand by industry | –0.66 | –0.62 | –0.69 |
| Total energy use | –2.58 | –2.52 | –2.63 |
| Scenario 2: TRN | $\sigma^{s4} = 0.3$ (see Fig. 1) | $\sigma^{s4} = 0$ | $\sigma^{s4} = 0.6$ |
| Household fuel consumption | –34.74 | –44.44 | –24.12 |
| Fuel demand by industry | –1.18 | –1.45 | –0.88 |
| Total fuel use | –5.89 | –7.49 | –4.15 |
| Total household energy use | –17.49 | –22.48 | –12.03 |
| Energy demand by industry | –0.69 | –0.86 | –0.52 |
| Total energy use | –3.32 | –4.24 | –2.32 |

Note σ^{s2} and σ^{s4} are the elasticities of electricity and fuel demand respectively.

we see that consumers must almost double their efficiency of use from 2005 to 2030 to obtain the simulated reductions. For this reason, one important conclusion of our analysis is that a continuous, and soft, environmental long-term policy is preferable to a radical short-term policy. Our simulations and dynamic analysis show that gradual and small changes over a longer period – 25 years in our case – allow us to achieve large and difficult transformations.

Within this framework, and taking the environmental effects as a guideline, the following are the main insights of this paper. First, the reductions in the household use of electricity and/or fuel (Scenarios 1 and 2) by 2030 are above 20%, so we obtain declines in emissions associated with these uses of electricity and fuel close to 20%. Total household energy use falls by 30.55% by 2030 in Scenario 3 with improvements in electricity and household fuel usage. However, the reduction in energy use by 2030 for the Spanish economy is only 2.58% for Scenario 1, 3.32% for Scenario 2, and 5.93% for the integrated Scenario 3. We have similar results for emissions. Undoubtedly, these falls by 2030 are important, because they are around 12.5% of the 2030 EU objectives, but they are not sufficient to achieve the economy-wide objectives. Additional and significant technological changes are necessary in production technologies, which are responsible for more than 80% of GHG and SO_x emissions. Changes in consumption patterns are important and socially necessary, but only lower emissions from production activities will let us achieve the EU objectives. Demand-side policies, mainly involving consumers, are crucial steps on the road to low-carbon economies. Nevertheless, our results also show that these measures would be encompassed with improvements on the production side. In other words, the journey must proceed on the basis of broad societal commitments, including the participation of all the economic structures, institutions, and consumers.

Second, rebound effects are important and should be considered in the design and evaluation of environmental policy. As has been seen, and is common in the literature, improved efficiency in energy use in general supposes money saved by consumers, and the additional consumption or investment produces rebound effects. These economy-wide rebound effects are also quantified in this paper. The rebound effect of electricity and fuel use is 70.52% in Scenario 1 (electricity use), 51.01% in Scenario 2 (fuel use), and 55.85% in Scenario 3 (electricity and fuel use). Thus, rebound effects offset more than 50% of direct reductions. These effects are significant, and any environmental policy should take them into account. Moreover, all policies would have to carefully analyse their composition before being implemented. Additionally, all energy sources should be considered to implement efficiency improvements, and impacts on coal and gas cannot be neglected. For example, as seen in Table 6, the rebound effect in Scenario 1 increases household direct emissions, while in Scenario 2 it mainly reduces the emissions from production activity. These results determine that

improvements in efficiency should be implemented in all sectors and by all agents, so that the rebound effects would be diminished.

Third, since the rebound effects are due to the additional production and consumption induced by household savings, renewable resources should be promoted to counteract such increases in emissions and increase the positive effects of changes introduced by consumers themselves. This issue encourages an extension of the current study to address the state of renewable energy in Spain, as well as an analysis of methods to reduce rebound effects. Moreover, efforts to include renewable sources of energy in the industrial use of electricity are essential – and required sooner rather than later.

As expected, the hypothesis concerning the costs associated with the adoption of these improvements affect the size and the timing of the outcomes obtained, as well as the rebound effects. Nevertheless, our results suggest that positive impacts can also be expected in the medium term, under a reasonable hypothesis of cost adoption by households.

All in all, returning to our main question at the outset of the paper, we can conclude that changes in Spanish households, following the lead of larger strategies involving technological improvements in the electricity and transport sectors, can lead to significant reductions of emissions and energy use in society as a whole. Seen in this light, the voluntary efforts of every citizen, as part of society, although individually limited, should be considered in environmental policy, and should by no means be underestimated.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at <http://dx.doi.org/10.1016/j.enpol.2018.03.065>.

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